Effects of Key Operational Variables on Micronized-Magnetite Cycloning Performance

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In 1997, Custom Coals International completed a DOE contract to test the Micro-Mag Process at the continuous bench-scale at DOE's National Energy Technology Laboratory (NETL). As a follow up to these tests, NETL conducted two series of tests to confirm the Custom Coals results and to expand upon the effects of key operational variables on cyclone performance when using magnetite that is finer than conventional Grade E magnetite. This paper highlights the results of batch tests using a 10-cm (4-inch) diameter cyclone in which the variables were magnetite size, medium density, cyclone orifice sizes, and inlet pressure. The results show that fairly sharp separations (about 0.060-0.090 Ep) can be achieved on coal as fine as 300 x 25 micron (48 x 500 mesh) if magnetite that is only about twice as fine as Grade E is used at higher inlet pressures (greater than 138 kPa (20 psi)) with the right combination of cyclone orifice sizes.

Keywords: Dense-medium, cycloning, micronized, magnetite, performance

INTRODUCTION

In the early 1990's, DOE developed a fine-coal cleaning process it called the Micro-Mag Process in an effort to extend the operating range of dense-medium cyclones to well below the traditional 28 mesh bottom size (1). The process entails the use of "micronized" magnetite in formulating the dense medium as a way of allowing for the efficient separation and recovery of coal as fine as 500 mesh (25 microns). This process differs from conventional dense-medium cyclone operations in that the micronized magnetite is much finer in size consist. For example, the finest grade of conventional magnetite from one commercial supplier was nearly 100% less than 45 microns, with about 15% less than 5 microns, while "micronized" magnetite may be on the order of 100% less than 10 microns, with over 50% less than 5 microns.

NETL has conducted and documented several in-house R&D studies of various aspects of the micronized-magnetite cycloning technology, including micronized magnetite production, cycloning, medium recovery, and economics (2-10). Test programs were generally conducted under closed-loop, batch conditions.

At about the same time, Custom Coals International developed similar technology and in 1993 exclusively licensed DOE's Micro-Mag Process as part of their effort to commercialize the technology through DOE's Clean Coal Technology Program. Additionally, in 1995-97, as part of a DOE High Efficiency Preparation solicitation, Custom Coals International completed a cost-shared contract with DOE to evaluate and advance micronized-magnetite cycloning technology through the design, construction, and operation of a fully integrated, 227 kg/hr (500 lb/hr), continuous circuit consisting of feed classification, cycloning, and magnetite recovery at NETL's Solids Processing Research Facility (SPRF) in Pittsburgh (11, 12).

While the Custom Coals project demonstrated the feasibility of the technology at the continuous bench-scale with regard to feed classification, dense-medium cyclone separation, and magnetite recovery, it also recommended that additional dense-medium cyclone testing be conducted to verify some of the findings obtained in the long-term tests, fill in some data gaps still remaining, and examine the effects of key operational variables on performance, particularly magnetite size consist. This paper summarizes the results of such a follow-up study, conducted by NETL, using a closed-loop, batch-mode circuit in NETL's SPRF.

EXPERIMENTAL APPROACH

Test Matrix

A total of 40 tests were run, as shown in Tables 1 and 2, of which 30 were submitted for float-sink analysis of at least one size fraction in order to construct partition curves. The tests were conducted in two phases.

Phase I covered Tests 1-1 through 1-17 and focused on magnetite grade, medium density, and apex orifice size. In Phase I, tests 1-5, 1-8, and 1-10 were identical tests run on different days as a quality assurance (QA/QC) measure in order to determine the precision that could be expected for a set of cyclone performance data. For test 1-8, three sets of samples were collected from the product streams in a sequential fashion resulting in tests designated as 1-8A, 1-8B, and 1-8C. This was done in order to determine the degree of precision that could be expected as a result of the processing, handling, splitting, and analyzing of the samples.

Phase II was designed as a follow up to Phase I and covered Tests 2-1 through 2-23, focusing on cyclone inlet pressure and cyclone geometry. In Phase II, replicate tests (tests 2-2, 2-19, 2-21, and 2-23) were run to again measure the degree of precision among tests.

TABLE 1 Micronized-magnetite Cycloning Phase I Test Matrix

TEST NO.	OPERATING CONDITIONS						
	MAG GRADE	**FEED PRESSURE kPa (psi)**	**MEDIUM DENSITY (G/CC)**	**APEX ORIFICE cm (in)**	**INLET ORIFICE cm^2 (in^2)**	**PARTITION DATA 48X200M**	**PARTITION DATA 200X500M**
1-1	K	620 (90)	1.30	1.59 (0.625)	0.774 (0.120)		X
1-2	K	620 (90)	1.40	1.59 (0.625)	0.774 (0.120)	X	X
1-3	K	620 (90)	1.40	2.22 (0.875)	0.774 (0.120)		X
1-4	L	620 (90)	1.30	1.59 (0.625)	0.774 (0.120)		X
1-5	L	620 (90)	1.40	1.59 (0.625)	0.774 (0.120)	X	X
1-6	L	620 (90)	1.40	2.54 (1.00)	0.774 (0.120)		X
1-7	L	620 (90)	1.40	2.22 (0.875)	0.774 (0.120)		X
1-8A	L	620 (90)	1.40	1.59 (0.625)	0.774 (0.120)		X
1-8B	L	620 (90)	1.40	1.59 (0.625)	0.774 (0.120)		X
1-8C	L	620 (90)	1.40	1.59 (0.625)	0.774 (0.120)	X	X
1-9	L	138 (20)	1.40	1.59 (0.625)	2.42 (.375)	X	X
1-10	L	620 (90)	1.40	1.59 (0.625)	0.774 (0.120)		X
1-11	M	620 (90)	1.20	1.59 (0.625)	0.774 (0.120)		X
1-12	M	620 (90)	1.30	1.59 (0.625)	0.774 (0.120)		X
1-13	M	620 (90)	1.40	1.59 (0.625)	0.774 (0.120)	X	X
1-14	M	620 (90)	1.40	2.22 (0.875)	0.774 (0.120)		X
1-15	60X	620 (90)	1.30	1.59 (0.625)	0.774 (0.120)		X
1-16	60X	620 (90)	1.40	1.59 (0.625)	0.774 (0.120)	X	X
1-17	60X	620 (90)	1.40	2.22 (0.875)	0.774 (0.120)		X

TABLE 2 Micronized-magnetite Cycloning Phase II Test Matrix

TEST NO.	OPERATING CONDITIONS						
	MAG GRADE	FEED PRESSURE kPa (psi)	MEDIUM DENSITY (G/CC)	APEX ORIFICE cm (in)	INLET ORIFICE cm^2 (in^2)	PARTITION DATA 48X200M	PARTITION DATA 200X500M
2-1	60X	138 (20)	1.20	1.59 (0.625)	0.774 (0.120)		
2-2	60X	345 (50)	1.20	1.59 (0.625)	0.774 (0.120)	X	X
2-3	60X	620 (90)	1.20	1.59 (0.625)	0.774 (0.120)		
2-4	60X	138 (20)	1.20	2.22 (0.875)	0.774 (0.120)		
2-5	60X	345 (50)	1.20	2.22 (0.875)	0.774 (0.120)		
2-6	60X	620 (90)	1.20	2.22 (0.875)	0.774 (0.120)		
2-7	60X	138 (20)	1.20	2.22 (0.875)	2.42 (.375)		
2-8	60X	345 (50)	1.20	2.22 (0.875)	2.42 (.375)		X
2-9	60X	620 (90)	1.20	2.22 (0.875)	2.42 (.375)		
2-10	60X	138 (20)	1.20	1.59 (0.625)	2.42 (.375)	X	X
2-11	60X	345 (50)	1.20	1.59 (0.625)	2.42 (.375)	X	X
2-12	60X	620 (90)	1.20	1.59 (0.625)	2.42 (.375)	X	X
2-13	60X	138 (20)	1.30	1.59 (0.625)	2.42 (.375)	X	X
2-14	60X	345 (50)	1.30	1.59 (0.625)	2.42 (.375)	X	X
2-15	60X	552 (80)	1.30	1.59 (0.625)	2.42 (.375)	X	X
2-16	60X	138 (20)	1.30	1.59 (0.625)	0.774 (0.120)		
2-17	60X	345 (50)	1.30	1.59 (0.625)	0.774 (0.120)	X	X
2-18	60X	552 (80)	1.30	1.59 (0.625)	0.774 (0.120)	X	X
2-19	60X	345 (50)	1.20	1.59 (0.625)	0.774 (0.120)	X	X
2-20	60X	138 (20)	1.20	1.59 (0.625)	0.774 (0.120)		
2-21	60X	345 (50)	1.20	1.59 (0.625)	0.774 (0.120)	X	X
2-22	60X	552 (80)	1.20	1.59 (0.625)	0.774 (0.120)		
2-23	60X	345 (50)	1.20	1.59 (0.625)	0.774 (0.120)	X	X

Feed Coal

The coal used for this study was from the Pittsburgh #8 Seam located in Belmont Co., Ohio. Feed sample preparation was designed to produce equivalent 48 x 500 mesh coal samples to be used as feed for the dense-medium cyclone tests. The feed samples for Phase I and Phase II were prepared at different times using different portions of the same lot of raw coal. The raw coal was first ground to 48-mesh top size using a hammermill, followed by the addition of water to constitute a 30% solids slurry by weight. This slurry was then pumped to a classification circuit, where it went through a combination of classifying and screening to produce a 48 x 500 mesh size fraction. Analysis of a head sample showed the feed coal to have the size and washability characteristics presented in Table 3 below.

TABLE 3 Cyclone Feed Coal Characteristics

Size Distribution								
Mesh	**Weight**	**Cum. Wt.**	**Ash**	**Total S.**	**Py. S.**	**Cum. Ash**	**Cum. Total S.**	**Cum. Py. S.**
Plus 48	6.37	6.37	19.60	3.64	1.67	19.60	3.64	1.67
48 x 100	25.48	31.85	16.06	3.82	1.98	16.77	3.78	1.92
100 x 200	33.87	65.72	13.56	3.88	1.99	15.11	3.83	1.96
200 x 325	17.18	82.90	13.42	3.88	2.18	14.76	3.84	2.00
325 x 500	9.68	92.58	15.39	4.34	2.67	14.83	3.90	2.07
Minus 500	7.42	100	52.28	5.15	4.44	17.61	3.99	2.25
48 x 200 Mesh Washability Analysis								
Specific Gravity	**Weight**	**Cum. Wt.**	**Ash**	**Total S.**	**Py. S.**	**Cum. Ash**	**Cum. Total S.**	**Cum. Py. S.**
Fl - 1.30	44.4	44.4	2.62	2.45	0.13	2.62	2.45	0.13
1.30 - 1.40	32.81	77.21	7.63	3.16	1.01	4.75	2.75	0.50
1.40 - 1.60	9.87	87.08	20.51	4.96	3.22	6.54	3.00	0.81
1.60 - 1.90	3.17	90.25	38.23	6.36	4.65	7.65	3.12	0.95
1.90 - 2.40	1.76	92.01	58.44	7.64	6.69	8.62	3.21	1.06
Sk - 2.40	7.99	100	81.86	10.55	10.19	14.47	3.79	1.79
200 x 500 Mesh Washability Analysis								
Specific Gravity	**Weight**	**Cum. Wt.**	**Ash**	**Total S.**	**Py. S.**	**Cum. Ash**	**Cum. Total S.**	**Cum. Py. S.**
Fl - 1.30	44.46	44.46	2.09	2.28	0.05	2.09	2.28	0.05
1.30 - 1.40	30.56	75.02	5.73	2.57	0.47	3.57	2.40	0.22
1.40 - 1.60	8.26	83.28	16.19	3.69	2.56	4.82	2.53	0.45
1.60 - 1.90	2.99	86.27	31.42	6.05	4.66	5.75	2.65	0.60
1.90 - 2.40	2.27	88.54	53.62	9.84	6.58	6.97	2.83	0.75
Sk - 2.40	11.46	100	79.75	15.77	15.11	15.31	4.32	2.40

Magnetite

Four grades of finely ground magnetite were used for the test program: PennMag Grade K, PennMag Grade L, Pea Ridge Grade M, and Pea Ridge Grade 60x.

Grades K, L, and M were the same magnetites that were used by Custom Coals during their DOE project that was described earlier. Grade 60X was specially obtained for this project to provide a grade of magnetite with a size consist in between that of grades L and M. The particle size distributions for all four grades, as determined by Microtrac® analysis, are shown in Table 4 below, along with typical size consists for grade B and E magnetites that are used widely throughout the coal industry.

TABLE 4 Size Distributions of the Test Magnetites Compared to Commercial Grades B & E

Microtrac Size, µm	Grade B, % passing	Grade E, % passing	Grade K, % passing	Grade L, % passing	Grade 60X, % passing	Grade M, % passing
44.0	100.0	100.0	100.0	100.0	100.0	100.0
31.0	84.5	98.1	100.0	100.0	100.0	100.0
22.0	69.5	91.2	98.1	100.0	100.0	100.0
16.0	57.0	73.4	86.2	95.4	98.1	100.0
11.0	39.5	54.1	63.6	82.7	93.1	100.0
7.8	28.5	26.5	38.6	63.9	85.2	100.0
5.5	16.1	13.3	19.8	43.7	72.6	95.7
3.9	9.5	5.6	8.3	25.4	56.6	86.1
2.8	4.0	3.0	2.6	11.3	33.9	55.6
1.9	0.0	1.0	0.2	3.1	13.9	23.7
1.4	0.0	0.0	0.0	1.0	6.3	11.1
0.9	0.0	0.0	0.0	0.0	1.6	3.1
D50 (microns)	13.50	10.80	9.25	6.22	3.58	2.64

Cyclone Test Circuit and Procedures

Figure 1 shows the block flow diagram of the closed-loop, batch-mode circuit for dense-medium cyclone testing. A slurry of measured amounts of 48 x 500 mesh coal, magnetite, and water was prepared in a 303-liter (80-gallon) dense-medium cyclone feed sump to meet the desired test conditions for several tests. This slurry was pumped to a Krebs 10-cm (4-in) diameter cyclone. The overflow and underflow from the dense-medium cyclone were directed to a full-stream sampling box where timed samples of each stream were collected simultaneously.

Sample analysis was conducted on the 48 x 200 mesh and 200 x 500 mesh size fractions. In addition, for Phase I only, total sulfur and pyritic sulfur contents were obtained in order to gain insight into pyrite reduction efficiency. Also, for select samples, float-sink analyses were conducted at specific gravities of 1.30, 1.40, 1.60, 1.90, and 2.40. Selection of the tests for this analysis was based on calculated Btu recovery/ash reduction results and a desire to highlight the effects of specific operating conditions.

Performance Evaluation Methodology

There are many different parameters one can look at in trying to draw conclusions about the effects of certain variables on cyclone performance. For this study we elected to evaluate the data using two performance measures -- the Separation Efficiency Index (SEI) and the Probable Error (E_P) value. It must be emphasized that SEI values are coal and specific gravity of separation (SG50) specific, whereas Ep values are equipment specific, but for the various reasons explained below, both had their advantages for application in this study.

The SEI is defined as: (Yield% x Refuse Ash%) / (Clean Coal Ash%). It is a measure of the sharpness of separation based on the grade and recovery of the products in relation to the feed, and it varies with location on the washability curve, generally being highest at the curve's elbow.

The partition curves and the curve-derived performance parameters, including E_P and SG50, presented in this report were generated using laboratory float-sink data and a Weibull-based, curve-fitting mathematical function applied through the Solver routine as found in the Microsoft Excel spreadsheet software. In a brief study related to this project (13), Science Applications International Corporation and NETL researchers found that the curve-fitting mathematical function technique provided for a fairly accurate and, more importantly, unbiased and consistent methodology for generating the partition curves and the curve-derived performance parameters.

In this report, the approach taken was to use the coal-specific Separation Efficiency Index as the main evaluation criterion for the summary analysis, even though the equipment-specific partition curve performance characteristics are the preferred approach. The rationale was that:

1) while the partition curves generated from the data points seemed to be generally smooth, the inherent difficulty in performing washability analysis on coal as fine as 48 x 500 mesh, particularly the 200 x 500 mesh fraction, makes for some questionable results and inconsistencies;

2) partition curves were generated only for selected tests, and some of those ended up being unusable, while the SEI can be applied to the entire set of tests, thereby providing a better picture of the effects of the variables.

Thus, the results will be discussed primarily on the basis of SEI, using the partition curve performance characteristics as reinforcement where possible. As pointed out earlier, it is recognized that the SEI has its own limitations, but it was felt that the SEI is indicative of the sharpness of separation when used to compare results from a single coal. Higher numbers indicate a sharper separation, with an SEI of about 900 being the optimum for the 48 x 200 mesh size fraction according to its washability analysis, and an SEI of about 1200 being the optimum for the 200 x 500 mesh size fraction.

TEST RESULTS

For each of the two phases of testing, there are two tables at the end of the paper that summarize the results. The first table for each phase, entitled Separation Efficiency (A1 and A3), presents the results from the direct analysis of the cyclone products (ash, sulfur, yield, Btu recovery, ash and sulfur reduction) and includes the SEI.

The second table in the set is entitled Partition Curve Results (A2 and A4) and is a summary of the performance characteristics of those selected tests that were subjected to float-sink analysis in order to formulate a partition curve to determine Ep and SG50.

Information from all of these tables was used as the basis for the following graphs and discussion. It is worth noting that these data include slight corrections to the SG50 data found in NETL's more detailed research report as a result of discovering a programming error (15). Also, it may be useful to review the data in relation to that of recent publications on the subject (16).

Phase I Performance Evaluation

Effect of Magnetite Grade:

1) For both size fractions (48 x 200 mesh, and 200 x 500 mesh), for a given set of operating conditions, the Grade M magnetite (2.6 microns) almost always produced the worst separations in terms of the SEI (as seen in Figures 2 and 3), as well as Ep. The Grade M tests at medium densities of 1.30 and 1.40 were marked by a visually evident increase in slurry viscosity that likely inhibited the efficiency of the separation. However, the separation achieved using the Grade M magnetite at a lower medium density of 1.20 was nearly comparable to that achieved using the Grade L and 60X magnetites.

2) For both size fractions, at both a 1.30 and 1.40 medium density, the Grade L (6.2 microns) and 60X (3.6 microns) magnetites produced the best results in terms of the SEI, also shown in Figures 2 and 3, when using the 1.59 cm (0.625 in) apex. This was also true for the Ep and SG50 values However, the slightly coarser Grade K produced similar results for the larger 48 x 200 mesh fraction at a 1.40 medium density in terms of separation efficiency for both the 1.59 cm (0.625 in) and 2.22 cm (0.875 in) apexes.

Effect of Apex Size:

1) For both size fractions, for a given grade of magnetite, the use of the smaller 1.59 cm (0.625 in) apex diameter almost always produced the lowest Ep values and the highest SEIs (see Figures 2 and 3). The exception was Grade K magnetite, which showed little effect with changing apex size.

2) As was expected, the larger 2.22 cm (0.875 in) apex resulted in lower SG50s at the expense of higher Eps.

Phase I Performance Summary:

1) For the 48 x 200 mesh fraction, at the constant conditions of 620 kPa (90 psi) inlet pressure with a 0.774 cm^2 (0.120 in^2) inlet, the best results were obtained using the smallest apex diameter (1.59 cm (0.625 in)) at a medium density of 1.30 or 1.40. For tests run at these conditions, the Grade K, L, and 60X magnetites all produced roughly the same separation efficiency with the better tests achieving ash reductions of 40-50% at greater than 95% kJ (Btu) recovery.

2) Also for the 48 x 200 mesh size fraction, from the partition curve analyses completed, test 1-16 using Grade 60X magnetite, a 1.59 cm (0.625 in) apex, at a medium density of 1.40 produced the lowest Ep value at 0.061 with a SG50 of 1.64.

3) For the 200 x 500 mesh size fraction, at the constant conditions of 620 kPa (90 psi) inlet pressure with a 0.774 cm^2 (0.120 in^2) inlet, the best results in terms of SEI and Ep were tests 1-4, 1-5, 1-15, and 1-16 that were run using the 1.59 cm (0.625 in) apex at a 1.30 or 1.40 medium density, and Grades L or 60X magnetites. Probable error values ranged from 0.129 to 0.168 with SG50s from 1.70 to 2.03. The Grade K magnetite produced comparable probable errors of 0.155 to 0.160, but at high SG50s of about 2.22.

4) At the best conditions referenced above, pyritic sulfur reduction was excellent. For example, in test 1-4 for the 48 x 200 mesh size fraction, the pyritic sulfur was reduced from 1.78% to 0.71%, a 60% reduction at a 94% kJ (Btu) recovery. For the 200 x 500 mesh size fraction, the pyritic sulfur was reduced from 2.18% to 0.57%, a 74% reduction at a 95% kJ (Btu) recovery.

Phase II Performance Evaluation

Effect of Inlet Size:

1) For the 48 x 200 mesh size fraction, for a given operating pressure, the larger inlet, 2.42 cm^2 (0.375 in^2), generally produced only slightly higher SEI values than the smaller inlet 0.774 cm^2 (0.120 in^2), as shown in Figure 4. However, for the 200 x 500 mesh size fraction, this improvement was more pronounced at certain inlet pressures, depending on the medium density, as shown in Figure 5.

2) For the 48 x 200 mesh size fraction, comparable Ep values were achieved for either inlet size with Ep values ranging from 0.034 to 0.064 across the entire scope of operating conditions tested. Also, there was no apparent effect on SG50.

3) For the 200 x 500 mesh size fraction, comparing tests 2-15 and 2-18, approximately equal

Ep values of 0.118 and 0.135 were generated for the large and small inlet openings, respectively, as well as fairly equal SG50s of 1.71 and 1.76, respectively.

Effect of Medium Density

1) As seen in Figure 4, for the 48 x 200 mesh size fraction, any test run at a medium density of 1.30 produced a higher SEI value than any test run using a medium density of 1.20. For the 1.30 medium density tests, the SEIs ranged from approximately 570 to 900 compared to a range of 40 to 330 for the 1.20 density tests. As mentioned earlier, this is mainly due to the lower SG50s from the 1.20 medium producing inherently lower SEI values.

2) As seen in Figure 5, for the 200 x 500 mesh size fraction, for a given set of operating conditions, the 1.30 medium produced a higher SEI value than the 1.20 medium for most of the tests. Only when using the large inlet and a 138-kPa (20-psi) inlet pressure did the 1.20 medium density produce a significantly better separation, probably because the less severe conditions allowed for better stability of the more dilute medium.

Effect of Cyclone Geometry and Inlet Pressure

1) For both size fractions, the large inlet/small apex cyclone configuration generally produced higher SEI values compared to any of the other three configurations tested. However, in four instances the SEI value for the small inlet/small apex combination, at either a 345- or 620-kPa (50- or 90-psi) inlet pressure, approached (but never quite equaled) the SEI value obtained with the large inlet/small apex. As discussed earlier, tests with the large apex were generally inferior.

2) For the 200 x 500 mesh size fraction, the three highest SEI values were produced using a 1.30 medium density at either a 345- or 620-kPa (50- or 90-psi) inlet pressure. This is similar to the case for the 48 x 200 mesh size fraction where the two best runs were produced at a 620-kPa (90-psi) inlet pressure using a 1.30 medium density.

3) Little difference was found in Ep values for the 48 x 200 mesh size fraction, with Eps ranging from 0.034 to 0.064. Inlet pressure had little effect on SG50s.

4) For the 200 x 500 mesh size fraction, the tests run at a 1.20 medium density using the large inlet/small apex configuration produced essentially the same Ep values no matter what the inlet pressure. However, for the tests run at a 1.30 medium density, Ep values for the 200 x 500 mesh size fraction increased significantly as inlet pressure was decreased from 620 kPa (90 psi) to 345 kPa (50 psi) to 138 kPa (20 psi). SG50s increased only slightly with increasing inlet pressure.

Phase II Performance Summary:

1) The best results for Phase II for the 48 x 200 mesh size fraction were those tests run with

a 1.30 medium density, using a small or large inlet, small apex, at either 138, 345, or 620 kPa (20, 50 or 90 psi) inlet pressure (2-13, 2-14, 2-15, 2-16, 2-17, 2-18). Eps were between 0.034 and 0.051 with SG50s between 1.47 and 1.53. Similar tests at a 1.20 medium density were almost as good in terms of Ep, but with lower SG50s (1.31 to 1.34) and thus, lower SEIs.

2) The best results for Phase II for the 200 x 500 mesh size fraction were those tests run with a 1.30 medium density, using a large inlet and small apex, at either 345 or 620 kPa (50 or 90 psi) inlet pressure (2-14, 2-15), based on SEI and Ep.

CONCLUSIONS

1) The results confirmed those found by Custom Coals during their pilot plant study in that the Grade M magnetite is too fine and does not provide for separations as sharp as the other coarser grades of magnetite. This appears to be due to the high viscosities created by the ultrafine magnetite particles, particularly for medium densities 1.30 and greater.

2) Phase I testing resulted in the conclusion that any of the three coarser grades of magnetite (K, L, 60X) would be quite suitable for making very good separations on material in the 48 x 200 mesh size range.

3) Phase I testing also showed that Grades L and 60X magnetites produced better separations on the 200 x 500 mesh size fraction than the Grade K magnetite.

4) Both phases of testing confirmed that the best operating conditions for this coal and for these SG50s include the use of the 1.59 cm (0.625 in) apex diameter as opposed to the larger ones. Phase II testing further showed that the large inlet/small apex cyclone configuration produced the best separations. The choice of orifice sizes in any situation is somewhat dependent on the anticipated reject yield.

5) Phase II testing showed that when using the 60X magnetite, the tests with the higher 345- and 620-kPa (50- and 90-psi) inlet pressures consistently produced superior separations to those at 138 kPa (20 psi).

6) Based on both phases of testing, the optimum set of operating conditions includes a Grade L or 60X magnetite, an inlet feed pressure of greater than 138 kPa (20 psi)--possibly as high as 345-620 kPa (50-90 psi), and a cyclone configuration consisting of a large inlet orifice and a small apex orifice (in this case, for a 10-cm (4-in) diameter cyclone, a 2.42 cm^2 (0.375 in^2) inlet and a 1.59 cm (0.625 in) apex). Under these conditions, excellent separations can be achieved, with probable errors in the approximate range of 0.035 to 0.050 for the 48 x 200 mesh size fraction, and in the approximate range of 0.120 to 0.140 for the 200 x 500 mesh size fraction.

7) Finally, the results reaffirm that sharp separations can be made on finer coal, such as 48

x 500 mesh, than is conventionally cleaned by using a “semi-micronized” magnetite that is finer than conventional magnetite, but is not completely in the 0-5 micron range. For example, conventional Grade B & E magnetites may have a D50 particle size of 11 to 14 microns, and are used to clean coal size fractions from 1.27 cm (0.5 in) top size down to 28 or 100 mesh, with overall Eps probably in the range of 0.020 to 0.060, depending on size consist and operating conditions.

However, in this study and the Custom Coals pilot plant study referenced, it was shown that a significantly finer 48 x 500 mesh feed coal could be cleaned using magnetite with a D50 particle size of 4 to 9 microns (roughly half the size of conventional magnetite) with overall Eps in the range of 0.060 to 0.090. In addition, excellent pyritic sulfur reduction was achieved even down to 500 mesh. It is also important to note that the Custom Coals study demonstrated that magnetite in this size range could be easily recovered with high purity with conventional magnetic separator circuits.

DISCLAIMER

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TABLE A1 Phase I Test Results -- Separation Efficiency

TEST NO.	OPERATING CONDITIONS					CYCLONE PERFORMANCE RESULTS									
						48 X 200 MESH FRACTION					200 X 500 MESH FRACTION				
	MAGNETITE GRADE	INLET (cm^2)	MEDIUM DENSITY (g/cc)	APEX DIAMETER (cm)	INLET PRESSURE (kPa)	WT YIELD (%)	CLEAN COAL ASH (%)	REJECT ASH (%)	PYR. S. REDUC. %	SEP. EFF. INDEX	WT YIELD (%)	CLEAN COAL ASH (%)	REJECT ASH (%)	PYR.S. REDUC. %	SEP. EFF. INDEX
1-1	K	0.774	1.30	1.59	620	87.26	7.28	47.26	41.13	566	86.76	7.00	44.05	42.14	546
1-2	K	0.774	1.40	1.59	620	92.23	7.54	72.90	41.53	892	90.74	8.00	57.80	29.39	656
1-3	K	0.774	1.40	2.22	620	93.04	6.56	58.97	37.59	836	88.35	6.02	45.35	63.31	666
1-4	L	0.774	1.30	1.59	620	88.02	5.96	54.91	60.19	811	89.40	5.56	58.80	73.89	945
1-5	L	0.774	1.40	1.59	620	91.90	6.81	65.93	49.87	890	90.80	6.02	60.10	71.41	906
1-6	L	0.774	1.40	2.54	620	84.17	5.86	48.62	66.04	698	74.48	4.99	30.44	87.39	454
1-7	L	0.774	1.40	2.22	620	84.67	6.27	55.03	61.91	743	77.55	5.37	41.18	78.38	595
1-8A	L	0.774	1.40	1.59	620	88.65	7.00	67.51	56.81	855	89.93	6.05	62.87	71.29	935
1-8B	L	0.774	1.40	1.59	620	91.90	7.10	66.25	48.49	858	91.91	6.27	62.04	64.58	909
1-8C	L	0.774	1.40	1.59	620	89.72	7.08	66.82	54.31	847	89.51	6.30	62.42	72.05	887
1-9	L	2.42	1.40	1.59	138	88.45	6.64	60.51	56.72	806	87.43	6.25	49.28	67.61	689
1-10	L	0.774	1.40	1.59	620	89.96	7.65	64.86	42.15	763	89.93	6.07	62.71	57.88	929
1-11	M	0.774	1.20	1.59	620	41.90	3.97	21.54	63.22	227	78.08	4.67	36.61	69.47	612
1-12	M	0.774	1.30	1.59	620	80.66	5.40	37.66	48.72	563	85.59	5.50	43.56	59.84	678
1-13	M	0.774	1.40	1.59	620	86.67	6.81	56.55	17.34	720	87.24	6.66	45.01	64.73	590
1-14	M	0.774	1.40	2.22	620	72.30	5.87	22.58	51.07	278	65.64	6.34	22.03	69.24	228
1-15	60X	0.774	1.30	1.59	620	81.71	5.31	46.84	67.29	721	78.47	5.62	60.20	77.65	841
1-16	60X	0.774	1.40	1.59	620	88.70	6.24	60.77	53.90	864	82.15	6.62	72.46	56.24	899
1-17	60X	0.774	1.40	1.59	620	76.93	5.39	40.39	68.71	576	65.90	6.93	43.86	73.42	417

TABLE A2 Phase I Partition Curve Results

TEST NO.	OPERATING CONDITIONS					CYCLONE PERFORMANCE			
	MAGNETITE GRADE	INLET (cm^2)	FEED PRESSURE (kPa)	MEDIUM DENSITY (g/cc)	APEX ORIFICE (cm)	48 X 200 MESH		200 X 500 MESH	
						Ep	SG50	Ep	SG50
1-1	K	0.774	620	1.30	1.59	---	---	0.155	2.22
1-2	K	0.774	620	1.40	1.59	---	---	0.160	2.22
1-3	K	0.774	620	1.40	2.22	---	---	0.210	1.96
1-4	L	0.774	620	1.30	1.59	---	---	0.134	1.81
1-5	L	0.774	620	1.40	1.59	0.087	1.82	0.129	2.03
1-6	L	0.774	620	1.40	2.54	---	---	0.177	1.63
1-7	L	0.774	620	1.40	2.22	---	---	0.225	1.71
1-8A	L	0.774	620	1.40	1.59	---	---	0.144	1.97
1-8B	L	0.774	620	1.40	1.59	---	---	0.158	2.04
1-8C	L	0.774	620	1.40	1.59	0.083	1.75	0.152	1.98
1-9	L	2.42	138	1.40	1.59	0.094	1.72	0.259	2.03
1-10	L	0.774	620	1.40	1.59	---	---	0.133	1.96
1-11	M	0.774	620	1.20	1.59	---	---	0.152	1.62
1-12	M	0.774	620	1.30	1.59	---	---	0.220	1.77
1-13	M	0.774	620	1.40	1.59	0.107	1.68	0.237	2.04
1-14	M	0.774	620	1.40	2.22	---	---	0.346	1.60
1-15	60X	0.774	620	1.30	1.59	---	---	0.131	1.70
1-16	60X	0.774	620	1.40	1.59	0.061	1.64	0.168	1.97
1-17	60X	0.774	620	1.40	2.22	---	---	0.139	1.58

TABLE A3 Phase II Test Results -- Separation Efficiency

TEST NO.	OPERATING CONDITIONS					CYCLONE PERFORMANCE RESULTS							
						48 X 200 MESH FRACTION				200 X 500 MESH FRACTION			
	MAGNETITE GRADE	INLET (cm^2)	MEDIUM DENSITY (g/cc)	APEX DIAMETER (cm)	INLET PRESSURE (kPa)	WT YIELD (%)	CLEAN COAL ASH (%)	REJECT ASH (%)	SEP. EFF. INDEX	WT YIELD (%)	CLEAN COAL ASH (%)	REJECT ASH (%)	SEP. EFF. INDEX
2-1	60x	0.774	1.20	1.59	138	42.10	13.60	11.92	37	76.48	10.76	24.01	171
2-2	60x	0.774	1.20	1.59	345	40.03	3.64	24.5	269	75.93	5.46	48.88	680
2-3	60x	0.774	1.20	1.59	620	41.53	5.38	11.85	91	65.27	8.09	13.55	109
2-5	60x	0.774	1.20	2.22	345	5.10	12.69	20.34	8	54.92	11.86	35.53	165
2-6	60x	0.774	1.20	2.22	620	2.32	9.52	14.56	4	30.24	19.05	21.49	34
2-7	60x	2.42	1.20	2.22	138	12.25	3.58	15.89	54	43.19	8.28	16.79	88
2-8	60x	2.42	1.20	2.22	345	4.02	4.37	14.70	14	36.92	4.69	17.56	138
2-9	60x	2.42	1.20	2.22	620	4.27	8.38	13.58	7	36.23	4.04	13.46	121
2-10	60x	2.42	1.20	1.59	138	45.18	3.91	20.91	242	62.63	4.39	61.46	877
2-11	60x	2.42	1.20	1.59	345	55.07	4.28	25.78	332	85.87	5.53	41.02	637
2-12	60x	2.42	1.20	1.59	620	57.66	6.43	18.40	165	86.62	7.23	37.65	451
2-13	60x	2.42	1.30	1.59	138	83.8	4.93	45.49	773	78.0	15.71	43.40	215
2-14	60x	2.42	1.30	1.59	345	85.4	5.50	50.51	784	89.8	4.48	59.52	1193
2-15	60x	2.42	1.30	1.59	552	88.7	5.41	55.08	903	91.8	4.66	60.24	1187
2-16	60x	0.774	1.30	1.59	138	77.7	4.96	36.55	573	74.7	4.64	24.21	390
2-17	60x	0.774	1.30	1.59	345	86.9	5.32	46.33	757	89.9	5.79	43.84	681
2-18	60x	0.774	1.30	1.59	552	88.0	5.34	50.10	826	92.0	4.47	51.87	1068
2-19	60x	0.774	1.20	1.59	345	58.2	3.60	23.88	386	82.2	4.33	37.61	714
2-20	60x	0.774	1.20	1.59	138	43.7	3.93	16.84	187	73.4	5.02	28.34	414
2-21	60x	0.774	1.20	1.59	345	63.2	3.58	22.86	404	84.7	7.39	39.53	453
2-22	60x	0.774	1.20	1.59	552	68.3	3.89	25.01	439	86.9	5.69	50.81	776
2-23	60x	0.774	1.20	1.59	345	61.6	3.89	23.20	367	82.3	5.58	36.36	536

TABLE A4 Phase II Partition Curve Results

TEST NO.	OPERATING CONDITIONS					CYCLONE PERFORMANCE			
	MAGNETITE GRADE	INLET (cm^2)	FEED PRESSURE (kPa)	MEDIUM DENSITY (g/cc)	APEX ORIFICE (cm)	48 X 200 MESH		200 X 500 MESH	
						Ep	SG50	Ep	SG50
2-2	60X	0.774	345	1.20	1.59	0.064	1.31	NA	1.74
2-8	60X	2.42	345	1.20	2.22	NA	NA	NA	1.32
2-10	60X	2.42	138	1.20	1.59	0.061	1.32	0.132	1.33
2-11	60X	2.42	345	1.20	1.59	0.047	1.34	0.136	1.65
2-12	60X	2.42	620	1.20	1.59	0.051	1.34	0.142	1.66
2-13	60X	2.42	138	1.30	1.59	0.034	1.47	NA	1.55
2-14	60X	2.42	345	1.30	1.59	0.043	1.51	0.161	1.66
2-15	60X	2.42	552	1.30	1.59	0.051	1.53	0.118	1.71
2-17	60X	0.774	345	1.30	1.59	0.044	1.50	NA	1.81
2-18	60X	0.774	552	1.30	1.59	0.049	1.52	0.135	1.76
2-19	60X	0.774	345	1.20	1.59	0.050	1.36	0.166	1.62
2-21	60X	0.774	345	1.20	1.59	0.042	1.36	0.214	1.65
2-23	60X	0.774	345	1.20	1.59	0.038	1.36	0.162	1.62

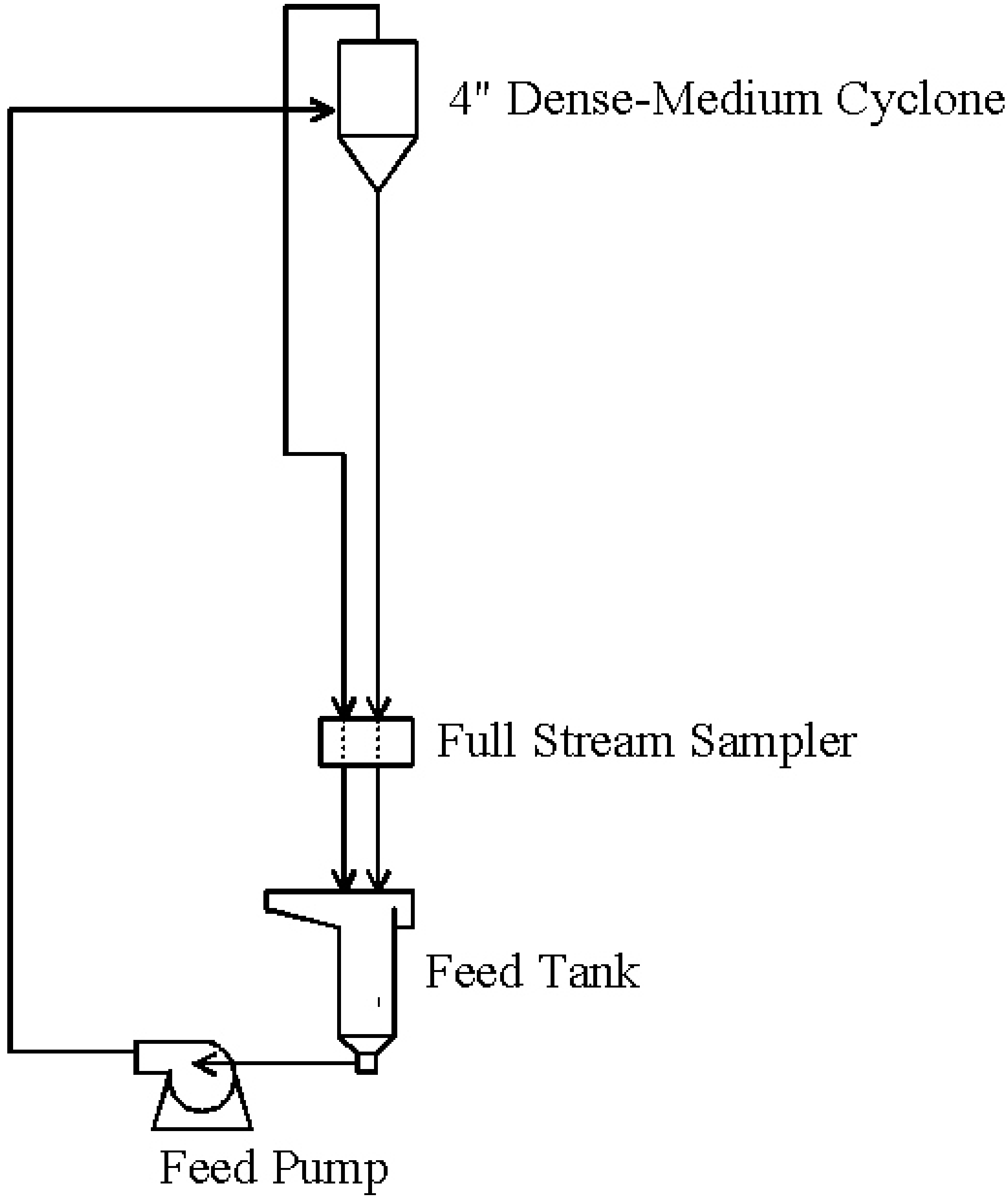
FIGURE 1 Flow Diagram of the Closed-Loop Dense-Medium Cyclone Circuit.

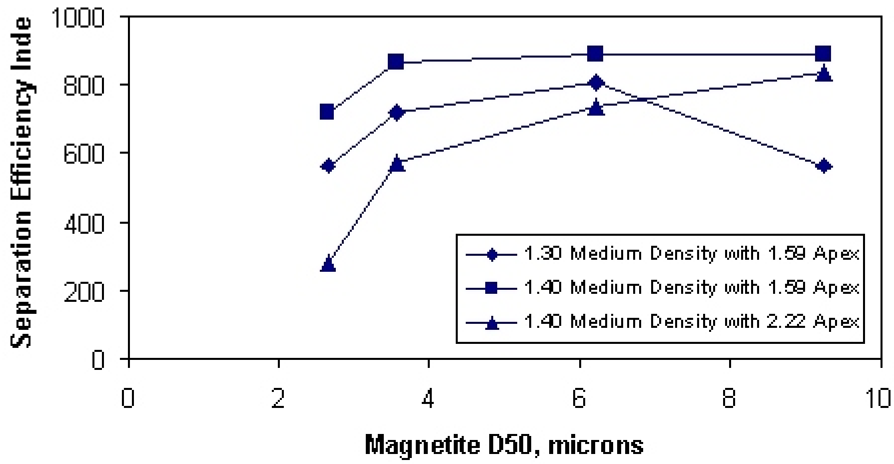
FIGURE 2 Effect of magnetite particle size on separation efficiency of the 48 x 200 mesh size fraction.

FIGURE 3 Effect of magnetite particle size on separation efficiency of the 200 x 500 mesh size fraction.

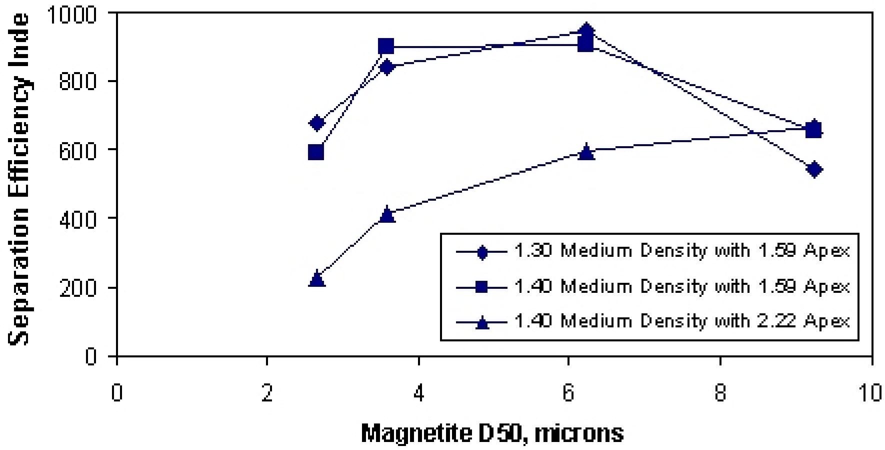
FIGURE 4 Effect of cyclone inlet pressure on separation efficiency of the 48 x 200 mesh size fraction.

FIGURE 5 Effect of cyclone inlet pressure on separation efficiency of the 200 x 500 mesh size fraction.

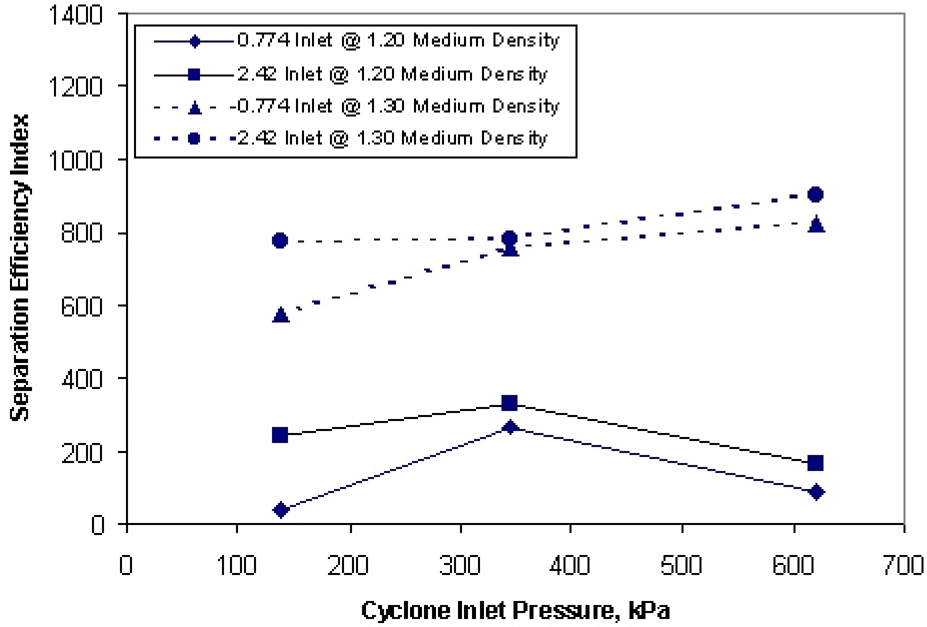

4" Dense-Medium Cyclone
Full Stream Sampler
Feed Tank
Feed Pump



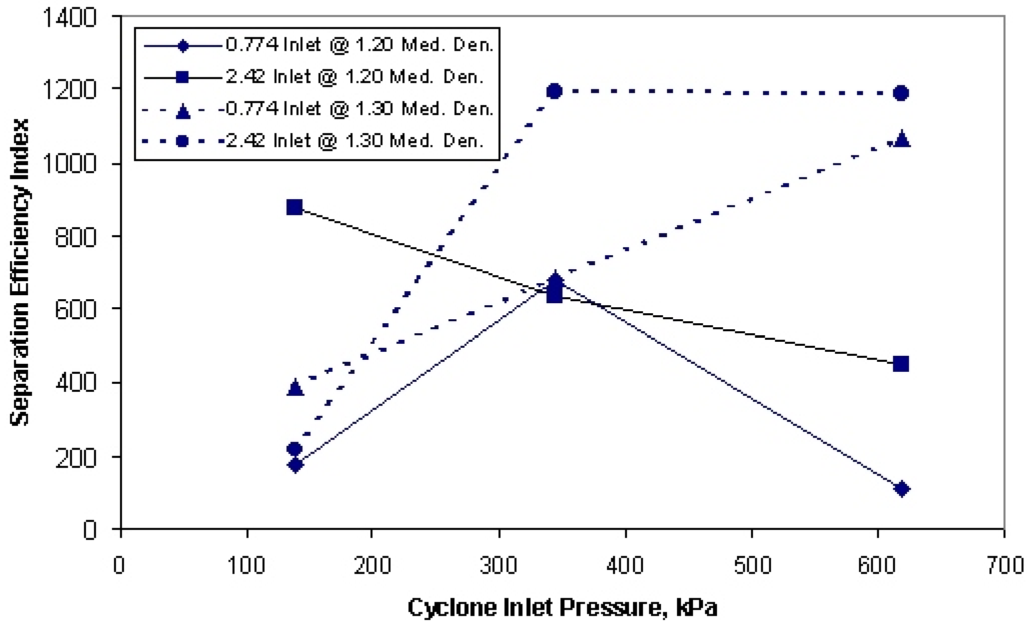
Separation Efficiency Inde
1000
800
600
400
200
0
0
2
4
6
8
10
Magnetite D50, microns
1.30 Medium Density with 1.59 Apex
1.40 Medium Density with 1.59 Apex
1.40 Medium Density with 2.22 Apex



Separation Efficiency Inde
1000
800
600
400
200
0
0
2
4
6
8
10
Magnetite D50, microns
1.30 Medium Density with 1.59 Apex
1.40 Medium Density with 1.59 Apex
1.40 Medium Density with 2.22 Apex



0.774 Inlet @ 1.20 Medium Density
2.42 Inlet @ 1.20 Medium Density
-0.774 Inlet @ 1.30 Medium Density
2.42 Inlet @ 1.30 Medium Density
Separation Efficiency Index
0
200
400
600
800
1000
1200
1400
0
100
200
300
400
500
600
700
Cyclone Inlet Pressure, kPa



Separation Efficiency Index
Cyclone Inlet Pressure, kPa
0.774 Inlet @ 1.20 Med. Den.
2.42 Inlet @ 1.20 Med. Den.
-0.774 Inlet @ 1.30 Med. Den.
-2.42 Inlet @ 1.30 Med. Den.
0
200
400
600
800
1000
1200
1400
0
100
200
300
400
500
600
700